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A new, light weight, six degrees-of-freedom, direct drive robot is studied in this project. The robot has a dual-arm, or a semi-parallel configuration, and it has the characteristics between those of a serial robot and those of a parallel robot. That is, it has a large payload-to-weight ratio and high stiffness of a parallel robot and a large workspace, compact structure, and simple control algorithm of a serial robot. Because of the use of direct drive motors and composite materials, the robot is light weight and has high precision. Different robot configurations are synthesized for different motion requirements. Motion and force analyses are carried out in the project, and motion simulation programs are completed. Possible army applications are explored.

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Final Report

Shih-Liang Wang

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B. STATEMENT OF THE PROBLEM STUDIED

To meet Army's demand for advanced robots in the battlefield, a new, light weight, six degrees-of-freedom, direct drive robot is studied in this project. The robot has a dual-arm, or a semi-parallel configuration, and it has the characteristics between those of a serial robot and those of a parallel robot. That is, it has a large payload-to-weight ratio and high stiffness of a parallel robot and a large workspace, compact structure, and simple control algorithm of a serial robot. Because of the use of direct drive motors and composite materials, the robot is light weight and has high precision.

The configurations of the semi-parallel robots are synthesized for different motion requirements. Position, velocity, acceleration analyses are performed for motion control. Degenerate configurations where rate control algorithms fail are analyzed. Uncertainty configurations when the robot gains a freedom are also discussed. Computer graphics are used to simulate motion control algorithms and delineate workspace boundaries. Force and torque analyses of the robots are also performed. Possible Army applications are explored.

C. SUMMARY OF THE MOST IMPORTANT RESULTS

C1. Synthesis of Robot Configurations

Six bar linkages are synthesized in this project for direct drive robots. The six bar linkage can be viewed as a semi-parallel configuration whose features are between those of a serial configuration and those of a parallel configuration. Previously only five bar linkage are used and investigated for robot configurations. Planar five bar linkages, as shown in Figure 1, are used for 2 dof planar motion [1,2,3,4], and spatial five bar linkages, as shown in Figure 2, are used for 3 dof spatial motion [5,6]. The six bar linkages studied in this project yield more degrees of freedom than those of five bar linkages do. Hence these new configurations are more versatile.

Six bar linkages for different robot configurations in this project are synthesized from two cooperating serial robots, as shown in Figure 3. When two grippers hold an object, they form a closed kinematic chain, i.e., a six bar linkage. If the two grippers are replaced by a coupler link, as shown in Figure 4, only a number of joints need to be active. The spatial linkage provides a light weight structure for the robots because all motors can be located at or near the base.

Figure 4 shows a 5 dof direct drive robot which provides a spatial translation and rotation, except the roll motion of the coupler arm [7]. A one dof roll motor can be mounted at the end of the coupler arm to accomplish the sixth degree of freedom.

Alternatively, the roll motion of the coupler arm can be achieved by adding an additional actuator to spin the upper right arm, as illustrated in Figure 5. The right shoulder then becomes a spherical joint. The added actuator will not roll the coupler arm independently. Instead the roll motion will be controlled by all three joints of the right shoulder [8].

The 5 dof robot can also be enhanced by introducing a prismatic joint on the right wrist, as illustrated in Figure 6. The added freedom can not control the roll motion. Instead, it can change the wrist distance, and therefore it is an internal or redundant dof. The redundancy can be used to simplify motion, to reduce energy consumption, to change the mechanical advantage, or to avoid obstacles and singularities [9].

A planar version of the 5 dof robot is shown in Figure 7. The planar robot has 3 dof, 2 dof in planar translation and 1 dof in rotation. A planar version of the redundant robot is shown in Figure 8. The planar versions of the 6 bar linkages are easy to visualize and analyze.

C2. Workspace Analysis

The reachable workspace of the planar 3 dof robot is shown in Figure 9. The workspace boundary is composed of arcs of circles and coupler curves of four bar linkages. At the boundary of the workspace, two of the three active joints will be fixed, and the six bar linkage is reduced to a 4-bar linkage. The four bar linkage, which has one dof, will be used to trace the coupler curve as a part of the reachable workspace. The four bar linkage may be folded in some cases, and the coupler curves are degenerated to arcs of circles. The procedure to delineate the workspace of this robot is very similar to that of a serial robot. In the latter case, the workspace boundary is consist of arcs of circles. The serial robot reaches its boundary when all but one joints are fixed, and the serial link robot is temporarily reduced to a single link. The free joint traces an arc of a circle as a part of the workspace boundary.

The size of this reachable workspace is comparable with that of a serial robot. However, the usefulness of the workspace in terms of the dexterity needs to be addressed. The dexterous workspace of a robot manipulator is defined as a region inside the reachable workspace where the robot can reach any point from any orientation. There is no dexterous workspace in this semi-parallel robot. Nevertheless, we can find the range of the orientation angle. As illustrate in Figure 10, for a specific hand position inside the workspace, the range of pitch angle of the coupler arm is limited.

The range of the pitch angle is a function of the tool center point (TCP) position. For instance, when the TCP is at the boundary of the workspace, the pitch angle range is zero. If the TCP is near the base, the orientation angle is large. The pitch angle range is also a function of the coupler's length. If the coupler is short and the wrist distance is small, the pitch angle range is large.

C3. Motion Analysis

Position and velocity analyses of the semi-parallel robots are modeled after those of serial robots [7,8,9,10], instead of those of parallel robots. Therefore, these analyses are very straightforward. Degenerate configurations where rate control algorithms fail are identified. Uncertainty configurations where the robot gains a uncontrollable freedom in the mode change are also recognized. Programs to simulate motion algorithms and to trace workspace are written in QuickBasic on IBM PC.

For the redundant robot, the wrist distance b can be changed is decided based on the load and workspace. That is, for a low payload and large volume task, b should be small; for a heavy payload and limited workspace task, b should be large.

The redundancy can be used to simplify motion. For instance, if the end effector's motion is pure translation along the coupler-arm's direction, the right arm can be held stationary and the left arm will push or pull the end effector. This motion is simpler than moving both arms with a fixed wrist distance. Moreover, the total energy consumption is less with a stationary right arm.

The redundancy can also be used to avoid singularities of the right arm and to avoid obstacles. Also, since the right wrist can be moved along the coupler arm freely. Mode change of the right arm between a outward posture and inward posture is possible.

C4. Force/Torque Analysis

A comparison of the force/torque requirements can be made between a serial and a semi-parallel robot under an external force, as shown in Figure 11. In a serial configuration (only one arm), the wrist will experience a torque and a force. On the other hand, in a semi-parallel configuration (two arms), the two wrists will experience reaction forces only. Therefore the two wrists can be left passive. This analysis in statics compliments the mobility analysis in kinematics.

In addition to the reduced load on the wrists, the torque loads on the inboard joints (shoulders) are also reduced in a semi-parallel robot as compared to that of a serial robot. Furthermore, the stiffness and the bandwidth are also increased with the dual-arm structure. The better load distribution is the reason why we always use both hands to hold golf clubs, baseball bats, snow shovels, and leave rakes.

C5. Army Applications

As compared to serial link robots, features of the semi-parallel robot include:

1. High stiffness for high payload capacity.
2. High bandwidth for good control stability.
3. High precision with direct-drive motors.
4. Simple structure for easy maintenance and repair.
5. Light weight structure because all actuators are near the base.
6. Limited dexterity in pitch and yaw.

With the limitation in dexterity, this robot is unsuitable for many traditional industrial applications like spot welding and spray painting. On the other hand, with the stiff structure and heavy payload capability, this robot can be useful in the battlefield applications as:

1. Loading bombs in hostile environments, as in a chemical war.
2. Loading/unloading bombs from transportation trucks.
3. Disposing explosive ordinance, like large artillery shells.
4. Clearing area-denial munitions.

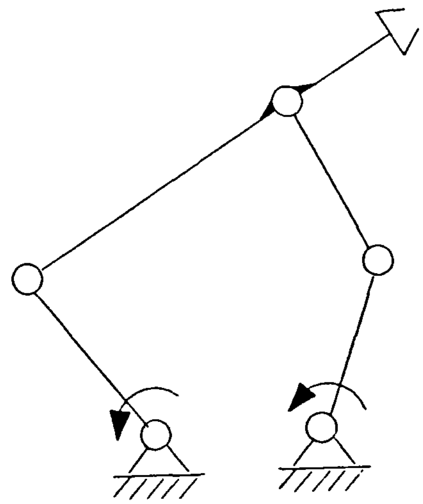
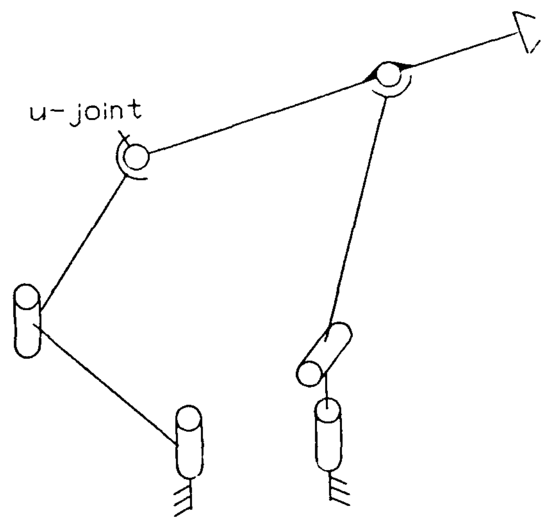


Figure 1



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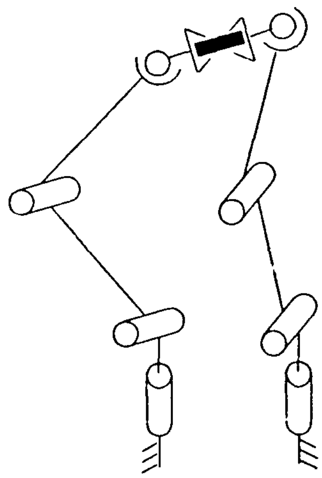

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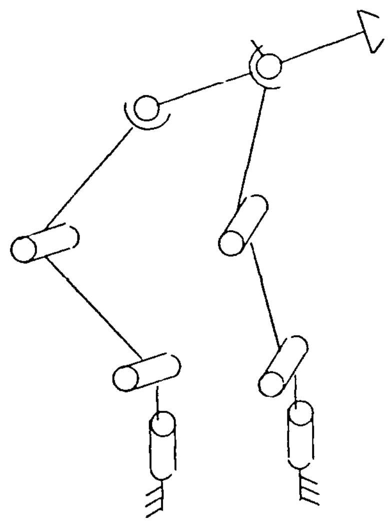

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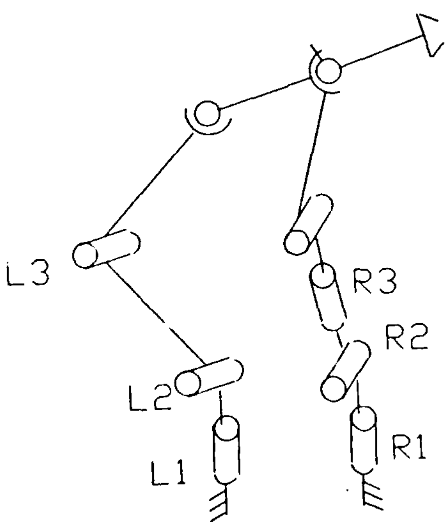

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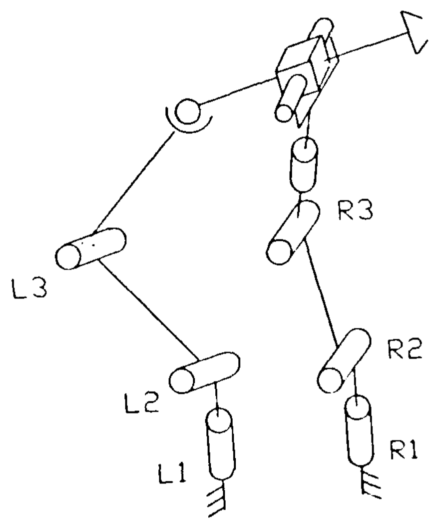

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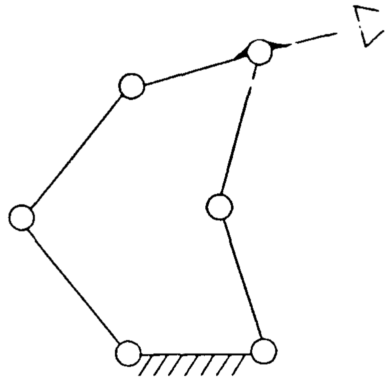

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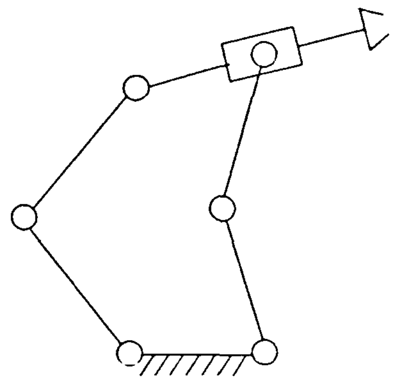

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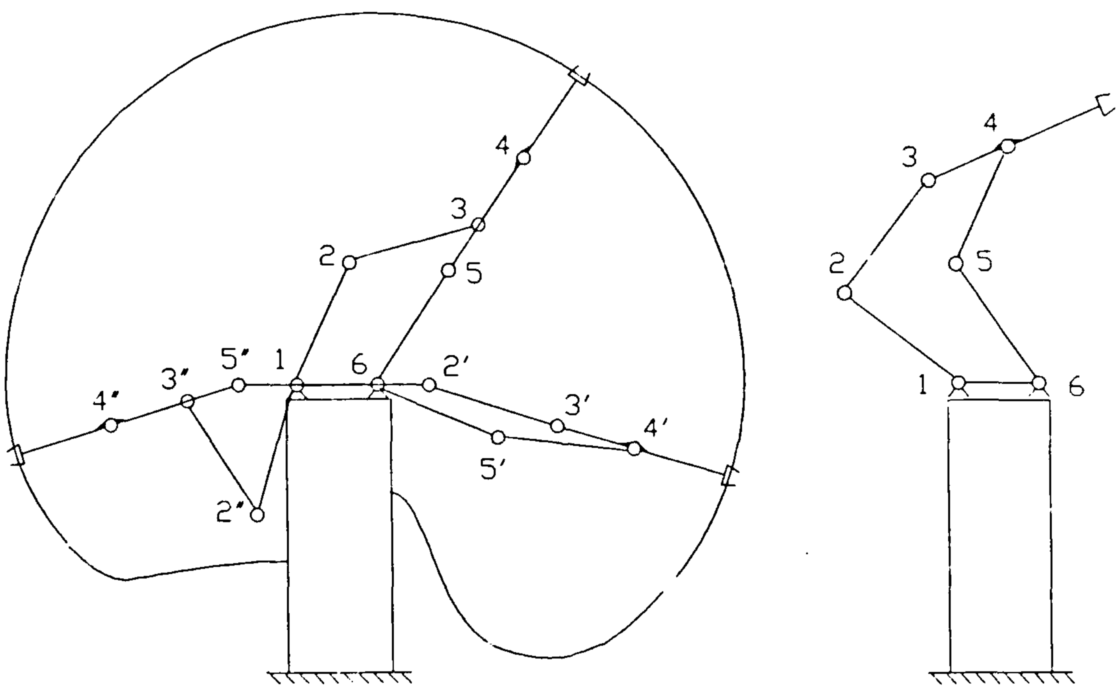

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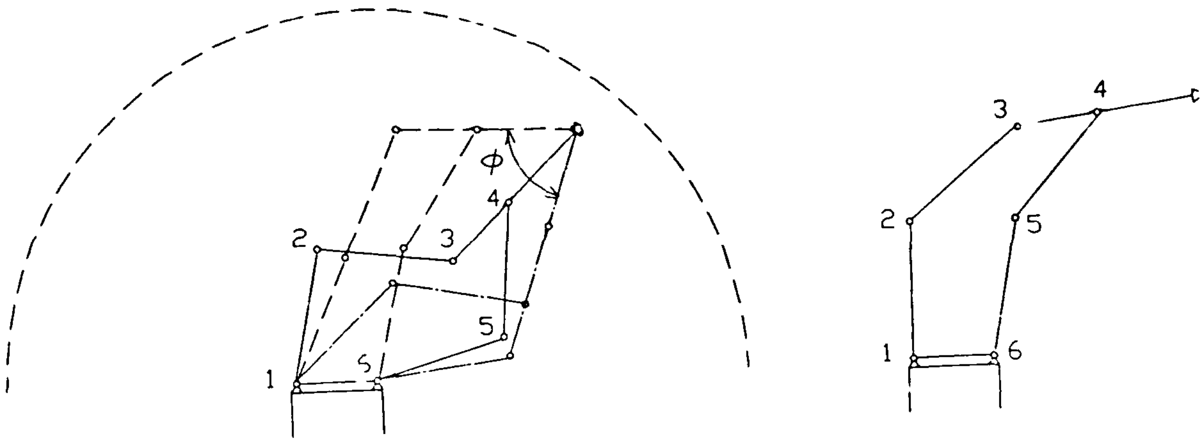

Figure 10

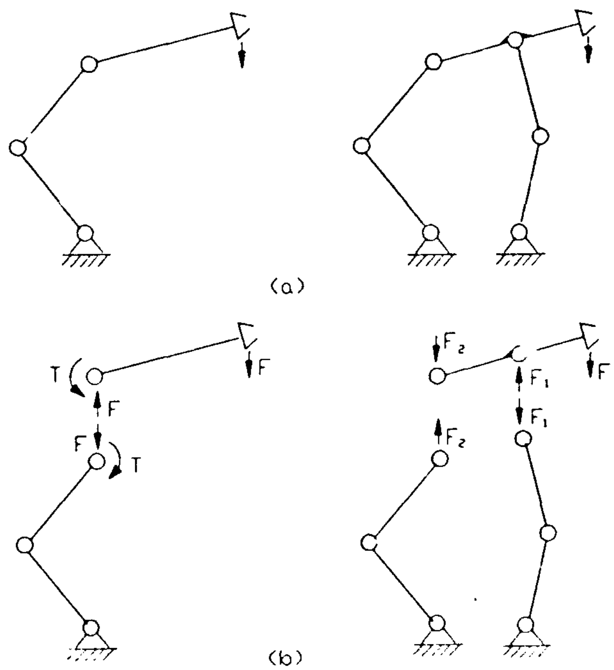

Figure 11

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E. LIST OF ALL PARTICIPATING SCIENTIFIC PERSONNEL

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2. Jingxi You, Graduate Research Assistant

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